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AD NUMBER
AD376654
CLASSIFICATION CHANGES
TO: unclassified
FROM: confidential
LIMITATION CHANGES
TO: Approved for public release, distribution unlimited
FROM: Distribution authorized to U.S. Gov't. agencies and their contractors; Critical Technology; SEP 1966. Other requests shall be referred to Air Force Rocket Propulsion Laboratory, Attn: RPPR/STINFO, Edwards AFB, CA 93523.
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MATERIAL AND PROCESSES R&D REPORT, STORABLE TOROIDAL COMBUSTOR DEMONSTRATION PROGRAM
VOLUME II

Rocketdyne, A Division of
North American Aviation, Inc.
6633 Canoga Ave.
Canoga Park, California

Technical Report AFRPL-TR-66-196

September 1966

Group 4
Downgraded at 3-Year Intervals
Declassified After 12 Years

Air Force Rocket Propulsion Laboratory
Research and Technology Division
Edwards Air Force Base, California
Air Force Systems Command
United States Air Force

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MATERIAL AND PROCESSES R&D REPORT,
STORABLE TOROIDAL COMBUSTOR
DEMONSTRATION PROGRAM
(1 June 1965 through 30 June 1966)

Volume II

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Air Force Rocket Propulsion Laboratory
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FOREWORD

(U) This material and processes R&D report was prepared under G.O. 8711 in compliance with Contract AF04(611)-10916, Part I, Para. B; and Line Items 9 and 10 of DD 1423. The development activities reported herein were accomplished during the period from 1 June 1965 through 30 June 1966. Rocketdyne report R-6678, Volume II has been assigned to this document.

(U) This report has been reviewed and is approved.

W. W. Wells
Project Engineer

ABSTRACT

(C) Regenerative cooling feasibility demonstrations were accomplished at 2000-psia chamber pressure with a 10,000-pound-thrust toroidal combustor using storable propellants with nitrogen tetroxide as the coolant. The coolant passages of the toroidal combustor were fabricated from Hastelloy-X tube material. An epoxy resin sealer material was used in the joints between the contoured walls and the end plates of the combustor, thereby preventing high-pressure hot-gas leakage.

(Confidential Abstract)

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ILLUSTRATIONS

INTRODUCTION

(C) The storable toroidal combustor program was initiated to demonstrate the feasibility of the regeneratively cooled high-chamber-pressure combustor segment. A segment of the baffled, annular, toroidal combustion chamber was selected for this feasibility demonstration. The segment operated at a nominal thrust level of 10,000 pounds and a chamber pressure of 2000 psia. N_2O_4/N_2H_4-UDMH (50-50) propellants were used at a nominal mixture ratio of 2 to 1.

(U) The primary goal of the program was to demonstrate regenerative cooling of the toroidal combustor segment. Hastelloy-X tube material was used for the coolant passages of the combustor segment. The segment was composed of two cooled, primary contoured walls and two cooled end plates. An epoxy resin seal was used between the end plates and contoured walls to seal against potential hot-gas leakage. This report is presented to discuss the Hastelloy-X and epoxy resin materials, the processes used in conjunction with these materials, and the operating conditions which they were subjected to during the feasibility evaluation testing. A more detailed discussion of the entire program is given in [illegible]

SUMMARY

(C) A toroidal combustor segment was selected for cooling feasibility demonstrations at 2000-psia chamber pressure using N_2O_4/50-percent N_2H_4+ 50-percent UDMH. The chamber configuration for this demonstration was designed for nitrogen tetroxide (oxidizer) regenerative cooling for the contoured walls which were fabricated from Hastelloy-X tubing. Oxidizer and/or water-cooled end plates were also used with the same type of tubing as the contoured walls.

(U) Tapering, contouring, and forming techniques were successfully used to obtain the desired contoured-wall and end-plate tube geometries. Contoured-wall and end-plate subassemblies were then created by furnace brazing the tubing and backup structure together. During the final assembly, an epoxy resin sealer material was employed in the joints between the contoured walls and the end plates, thereby sealing against potential high-pressure hot-gas leakage.

(C) Five cooled thrust chamber evaluation tests were conducted with the Hastelloy-X chamber. The first two tests, with water cooling, were completely successful. The third and fourth tests, with N_2O_4 regenerative cooling, were successful although some end-plate damage was incurred during the fourth test at 2025-psia chamber pressure. The fifth test was an attempted 20-second duration test using water cooling for the end plates and N_2O_4 regenerative cooling for the contoured walls. The water coolant valve failed to open until after the start of this test, causing severe damage to the chamber end plates. However, the contoured wall tubes suffered very little damage during the test which was terminated after 8.07 seconds of mainstage operation.

(C) Regenerative cooling feasibility with Hastelloy-X tubing was demonstrated during a 2-second duration test at a chamber pressure of 2025 psia. The epoxy resin material proved to be an acceptable seal during each of the five tests.

DISCUSSION

COOLED THRUST CHAMBER FABRICATION

(C) A two-dimensional, 10,000-pound-thrust combustor was selected for demonstrating cooling feasibility at 2000-psia chamber pressure. This combustor was comprised of two contoured walls and two parallel end plates spaced 3 inches apart. The throat section was rectangular with dimensions of approximately 1.1 by 3.0 inches. The plan view of the combustion zone may be approximated by a 6-inch-diameter circle; i.e., 6 inches from the injector face to the throat plane and 6 inches maximum between the contoured walls. A two-dimensional, deLaval-type nozzle with an area ratio of 5.65 to 1 and an expansion angle of 30 degrees, 15 degrees per side, was incorporated into the segment. An isometric drawing of the chamber is shown in Fig. 1.

(U) A nitrogen tetroxide regeneratively cooled tube bundle was utilized for the contoured walls. The coolant pressure drops and tube bundle geometry were designed for flight-type application. Oxidizer and/or water-cooled end plates were also used; however, no attempt was made to optimize the end-plate tubes for flight-type application. For the contoured-wall design, a parallel-pass cooling circuit was chosen where half of the total coolant passed simultaneously through each contoured wall. All of the coolant was then manifolded to the injector. The end plates like the contoured walls were designed primarily for nitrogen tetroxide cooling. Again, a parallel circuit was used to cool the end plates. Both contoured-wall and end-plate tubing were supplied from drilled passages at the injector end of the chamber. The coolant flow was, in turn, collected in similar drilled passages at the chamber exit end.

(U) Heat transfer, stress, and pressure drop analyses were conducted to determine tube materials and sizes for the cooled toroidal combustor. Because the maximum heat flux occurs in the throat region, the effort

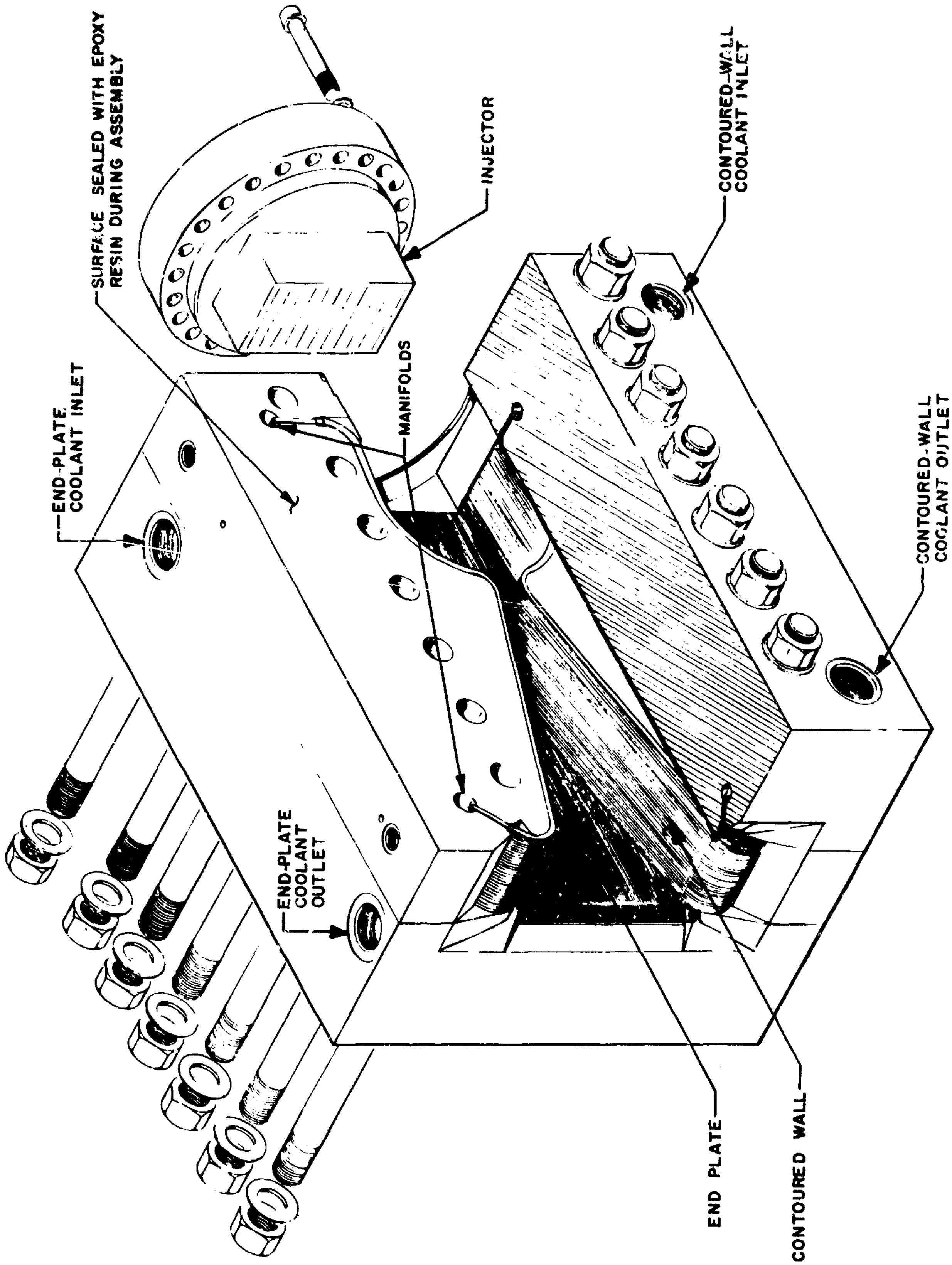

Figure 1. Cooled Toroidal Combustor

was concentrated in this area. Hastelloy-X appeared to be the most promising tube material for this cooling feasibility demonstration, and it was selected as the primary material for the cooled chamber contoured walls and end plates. The heat transfer and stress analyses fixed the tube wall thickness at 0.008 inch. Type 347 CRES tube material was selected for a backup chamber; however, it was not completed.

(U) Figure 2 shows the predicted (theoretical) heat fluxes for the contoured Hastelloy-X chamber walls using an estimated (Bartz) gas-film coefficient, a coolant-side coefficient with the curvature enhancement, and the 0.008-inch wall thickness. The computed maximum heat flux was approximately 41.5 Btu/in.^{2}-sec. A similar heat flux distribution was predicted for the end plates.

(C) Wall temperature predictions for both the gas and liquid sides were calculated for the tube contoured walls and end plates at the nominal 2000-psia chamber pressure. The maximum hot-gas-side wall temperatures were computed to be 1687 F and 1735 F for the contoured walls and end plates, respectively. The higher end-plate wall temperatures resulted from the absence of the curvature effect present in the contoured wall tube. The maximum liquid-side wall temperatures of the end plates and contoured walls were near 600 F. The bulk temperature rise of the nitrogen tetroxide coolant was computed as 155 F for the contoured walls and 79 F for the end plates. The predicted cooling characteristics of the Hastelloy-X chamber are summarized in Table 1.

(U) Two sizes of Hastelloy-X tubing were selected, 0.108 inch OD by 0.008 inch wall thickness for the end plates, and 0.168 inch OD by 0.008 inch wall for the contoured walls. Tapering and forming of this raw tubing was necessary to give the desired contour and coolant passage geometry (Fig. 3). End-plate tube tapering was from a 0.103 inch OD at the injector and exit ends to 0.070 inch OD for the throat region. Likewise, the contoured-wall tubes were tapered from a 0.162 inch OD (at both ends) to

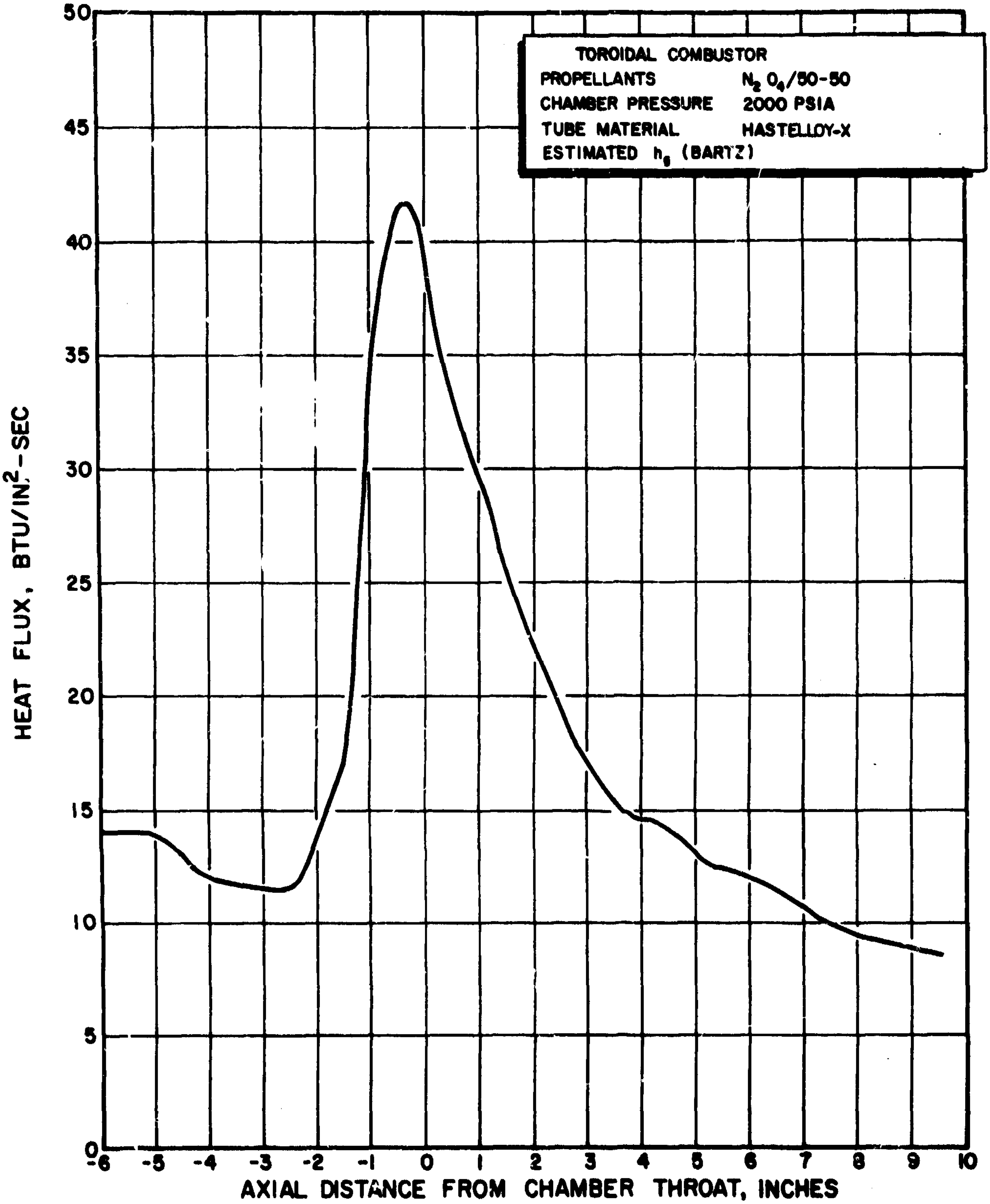

Figure 2. Contour Wall Heat Flux vs Chamber Length

TABLE 1

PREDICTED COOLING CHARACTERISTICS FOR THE STORABLE TOROIDAL COMBUSTOR

Hastelloy-X Tube Wall	Maximum Coolant Velocity, ft/sec	Maximum Heat Flux, Btu/in.-sec	Maximum Gas-Side Wall Temperature, F	Maximum Coolant Wall Temperature, F	Coolant Bulk Temperature, Rise, F	Coolant Pressure Drop, psi
Contoured	188	41.3	1687	644	155	615
End Plate	200	40.7	1735	526	79	1300

Gas Film Coefficient = Estimated (Bartz)

Chamber Pressure = 2000 psia

Coolant = Nitrogen tetroxide

Contoured Wall Coolant Flowrate = 12.9 lb/sec

End-Plate Coolant Flowrate = 25.8 lb/sec

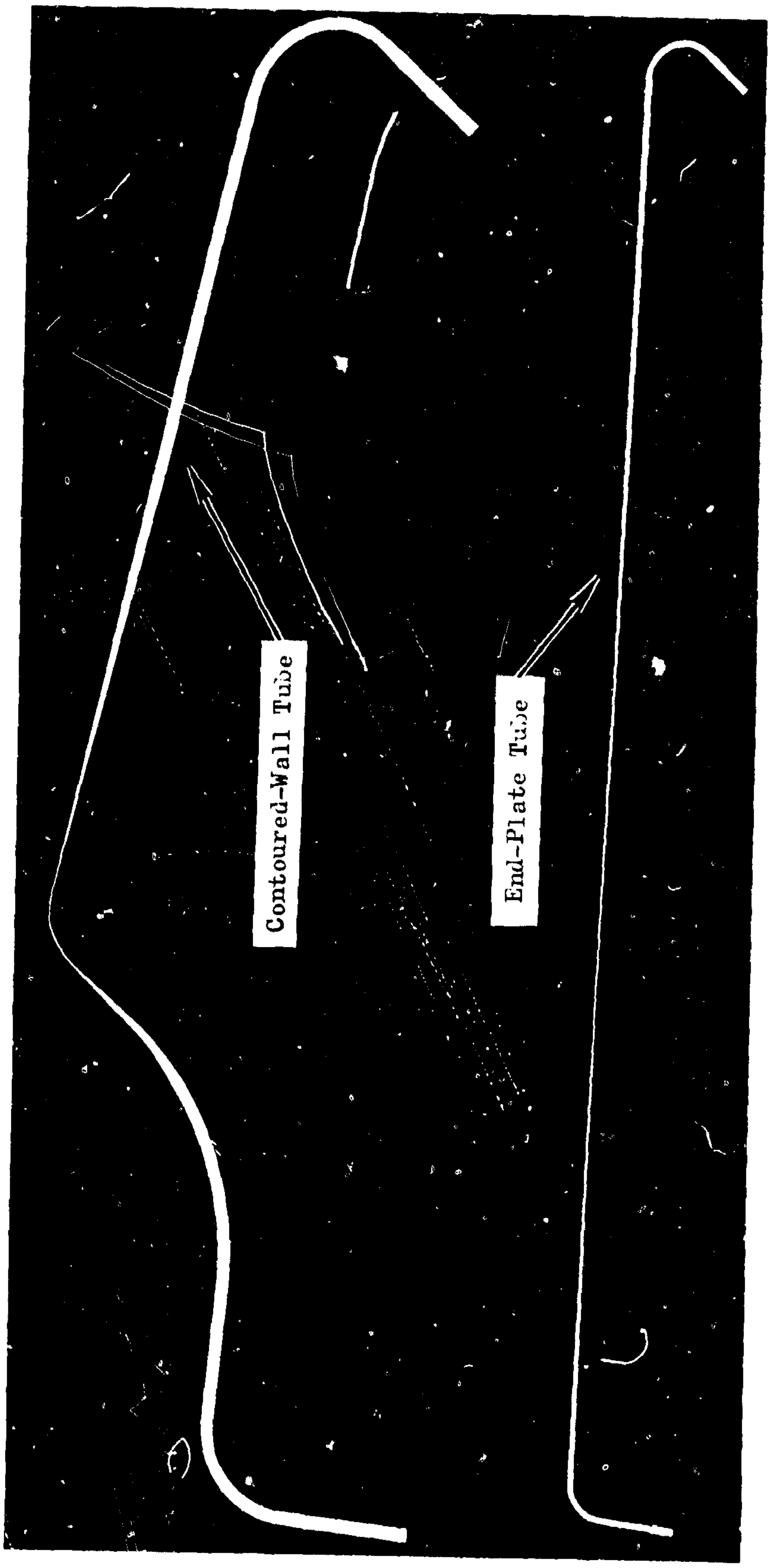

Figure 3. Typical Cooled Thrust Chamber Contoured-Wall and End-Plate Tubes

0.075 inch OD for the throat region. Both end-plate and contoured-wall tubes were formed to the desired contours and then "booked" (flattened between two book dies) to produce a constant width of 0.070 inch and a varying coolant passage flow geometry, as shown in Fig. 4. This 0.070-inch dimension represents the width exposed to the hot combustion products. Precision Sheet Metal Co. (PSM) was responsible for the tapering and forming.

(U) The raw Hastelloy-X tubing was welded and drawn from air melt stock and then eddy-current inspected to a 0.001 inch maximum defect level by Superior Tube Co. Samples of the raw tubing were metallurgically evaluated when received with the following results.

	0.168 OD by 0.008-Inch Wall	0.108 OD by 0.008-Inch Wall
Maximum Wall Thickness, inch	0.0083	0.0083
Minimum Wall Thickness, inch	0.0081	0.0081
Maximum OD Defect, inch	0.0002	0.0003
Maximum ID Defect, inch	0.0001	0.0001
Average ASTM Grain Size	8	8
Ultimate Tensile Strength	128,200	119,110
Yield Strength, 0.2 Percent Offset	81,500	70,400
Elongation, Percent in 2 Inches	38	36

(U) It was speculated that the high yield strength would necessitate annealing of the tubing prior to tapering; however, this was not the case. The end-plate tubes were fully tapered down to 0.070 inch without annealing, a 35 percent OD reduction. The contoured-wall tubes were partially tapered, annealed once and then finish tapered to 0.075 inch, a total OD reduction of 55 percent. Prior to forming, all of the tubing was annealed. Annealing was accomplished in a vacuum furnace at 2150 F for about 1-1/2 minutes. The tubes were hung vertically in the retort and fixtured so they would not touch each other. After annealing, the tubes were bright and lustrous.

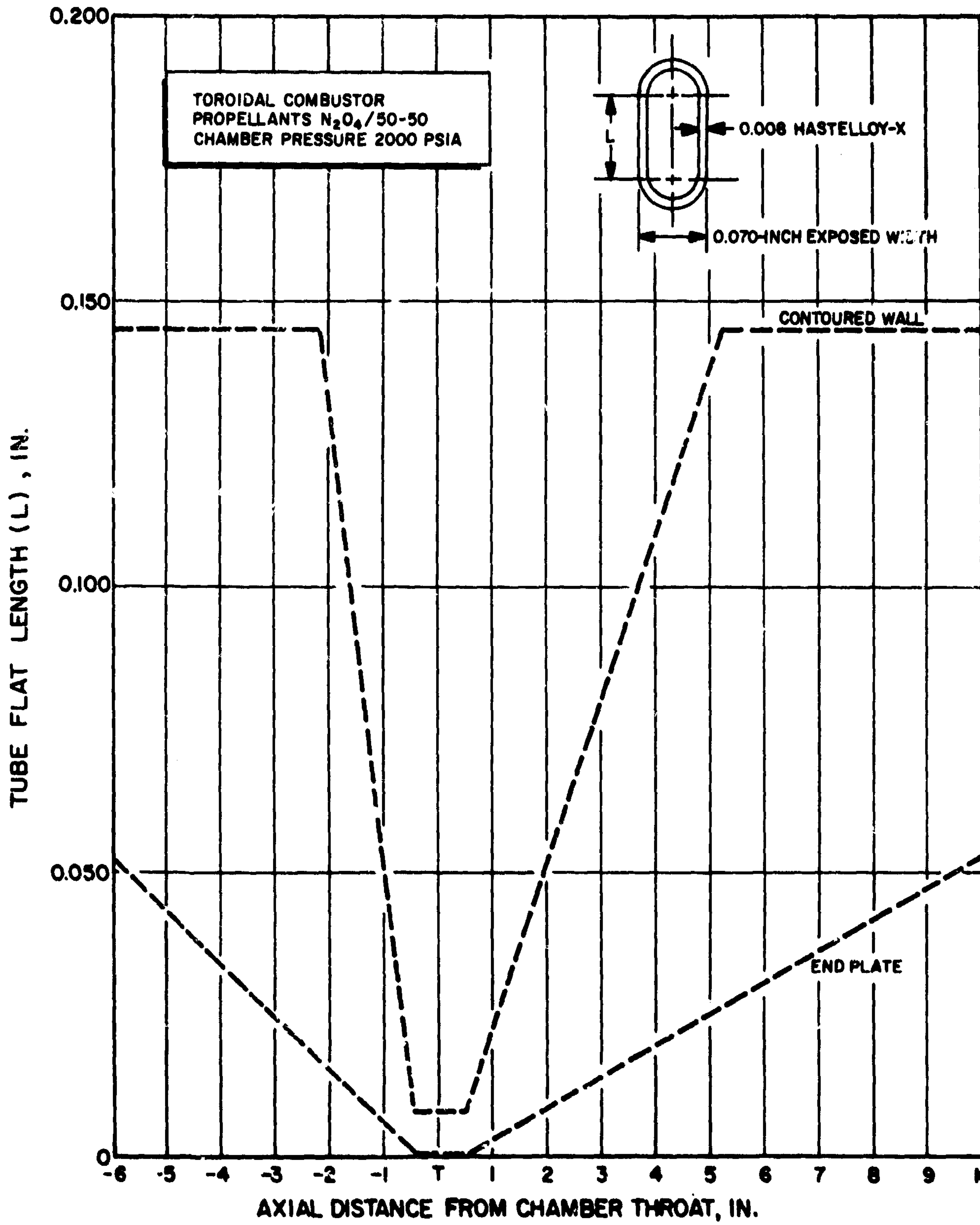

Figure 4. Tube Flat Length vs Chamber Length

(U) During selected stages in the tapering and forming operations, both the contoured-wall and end-plate tubes were microscopically examined for wall thickness and defects. Samples of the final end-plate tubes revealed: (1) a smooth OD with no defects, (2) a wall thickness of 0.0069 to 0.0072 inch in the area of maximum taper, (3) slight ID surface roughening, and (4) a wall thickness ranging from 0.0071 to 0.0079 inch in other areas of the tubes. Samples of the final contoured-wall tubes disclosed: (1) a wall thickness of 0.0076 to 0.0080 inch in the area of maximum taper, (2) moderate ID surface roughness, (3) no cracks or thinning at the bends, and (4) a wall thickness ranging from 0.0079 to 0.0082 inch in other areas of the tubes. All of the end-plate and contoured-wall tubes were subjected to a fluorescent penetrant inspection revealing only one contoured-wall tube with rejectable indications.

(U) Mechanical properties of the Hastelloy-X tubing were determined after annealing operations with the following results:

	Contoured Wall	End Plate
Ultimate Tensile Strength	117,000	115,000
Yield Strength, 0.2 Percent Offset	53,600	50,800
Elongation, Percent in 2 Inches	46.7	41

Hastelloy-X samples were subjected to a typical furnace braze cycle to determine if the mechanical properties changed. The conclusion was that the properties were not significantly affected by exposure to the furnace braze cycle.

(U) The assembly of the Hastelloy-X contour wall and end plate details (subassemblies) consisted of furnace brazing the coolant tubes to backup structural blocks. Material selection for the backup structure was commensurate with furnace brazing requirements; i.e., the backup structure and the tubes had similar thermal expansion coefficients. A structural joint was obtained between the tubes, and the block and a seal joint was

made between the tube ends and the manifolds. Nicoro (62-percent Cu/35-percent Au/3-percent Ni) alloy was used for the subassembly braze cycles. The tubing and structural blocks were nickel-plated (0.001 inch) and the tube ends were coated on the inside with boron nitride stopoff to prevent braze alloy plugging. After brazing, there were no leaks on the two contoured-wall subassemblies. There were several repairable tube-to-tube leaks and one tube-to-manifold leak on the end plates. One end plate had several tubes partially or completely plugged with braze alloy at the exit end. Most of the alloy was removed from the tube ends before the final assembly, although some of the tubes were still partially, but not seriously restricted.

(U) Because of problems encountered during final assembly furnace brazing of a 347 CRES assembly, it was decided not to braze the Hastelloy-X assembly but to use TR-69F, an epoxy resin compound, as a seal material. TR-69F is an ablating, flexible, room-temperature-curing organic material filled with asbestos fibers. It was previously used successfully as a hot-gas seal during several other programs. The chamber structural studs were designed to take all of the pressure loads so the TR-69F was not a structural material. The propellant manifold joints between the end-plate and contoured-wall blocks were sealed by using Viton A O-rings. The chamber was assembled by trowling the TR-69F onto the mating surfaces of the end plates and contoured walls and then placing these surfaces together. The structural studs were installed and torqued, squeezing out the excess material. The seal was allowed to cure in place. Leak checks revealed a good seal at all interfaces.

(U) The TR-69F is a nylonate phenolate, ablative, room-temperature-curing material made from equal parts of two components, A and B. Component A is a viscous liquid, component B is a thixotropic paste, and when mixed together they form a paste which is trowelable or can be applied by means of a cartridge or sealant gun. The minimum working life of the mixture

is 30 minutes, and the room temperature (77 F) curing time is within 24 hours. Typical mechanical and physical properties at room temperature after 24 hours are as follows:

Ultimate Tensile Strength, psi	700 minimum
Ultimate Elongation, percent	13 mimimum
Hardness, Shore "A"	85 minimum
Ablative Lap Shear Strength, psi	600 minimum
Specific Gravity	1.35 - 1.65
Thermal Conductivity, Btu/hr-ft-F	0.2
Thermal Expansion, in./in.-F	30×10^{-6}

The TR-69F material is manufactured by the Thermo-Resist Company, Burbank, California.

TEST RESULTS

(C) A series of five tests were conducted with the Hastelloy-X cooled thrust chamber and a self-impinging doublet injector. The primary objective of these tests was to demonstrate cooling feasibility at 2000-psia chamber pressure. The test series began with two tests where water was used as the coolant for both the end plates and the contoured walls. These tests were conducted for 0.33- and 2.04-seconds duration at chamber pressures 1632 and 1694 psia. The heat transfer analysis indicated that higher tube-wall temperatures could be expected if water cooling was used in place of N_2O_4 cooling. Water cooling at 1700-psia chamber pressure and N_2O_4 cooling at 2000-psia chamber pressure would result in approximately the same maximum hot-gas-side wall temperatures.

(C) After successfully water cooling the chamber, N_2O_4 cooling was in order. Two N_2O_4-cooled tests were conducted where the end-plate coolant was dumped overboard into a burn pit and the contoured-wall coolant was returned to the injector; i.e; regenerative cooling. End-plate and contoured-wall cooling was successfully accomplished during the first of these tests for 0.91 seconds at 1778-psia chamber pressure. During the

second N_2O_4-cooled chamber test, a chamber pressure of 2025 psia was achieved for 2.03 seconds of mainstage operation. The contoured-wall tubes were in excellent condition following this test, thereby demonstrating regenerative cooling feasibility at 2000-psia chamber pressure. Approximately 10 of the end plate tubes were eroded and leaking from splits or pinholes. The damage was centered on the tube crowns extending up to approximately 1 inch in length. These tube erosions and splits were indicative of a progressive material failure and not a sudden rupture from excessive internal pressure stresses. Erosion of this type usually results from insufficient cooling and/or oxidation. The cause of these end-plate tube failures is unknown; however, some related factors were: (1) no coolant curvature enhancement, i.e., the contoured wall tube cooling was enhanced by the throat curvature where the end plate tubes had no curvature, therefore the end-plate tubes would operate at a higher temperature, (2) the end plates were more prone to overheating and streaking compared to the contoured walls, and (3) in general, the damaged tubes correlated with those which were partially restricted with braze alloy during fabrication. All of this alloy was not removed.

(C) The fifth test was an attempted 20-second duration test with the Hastelloy-X chamber. Water cooling was used in the end plates and N_2O_4 regenerative cooling was used in the contoured walls. The water main valve failed to open and, consequently, end-plate cooling flow did not begin until about 200 milliseconds after the start of mainstage. At the high heat fluxes experienced, the uncooled tubes were almost completely burned away in the 200 milliseconds. After the end-plate tubes were damaged, the water began to flow and apparently film cooled the end plates and minimized further damage to the chamber during the remainder of the test. The total duration of this test was 8.07 seconds. The contoured-wall tubes were in very good condition (except for about 5 tubes adjacent to the end plates) following this test which, in effect, demonstrated N_2O_4 regenerative cooling feasibility at the chamber pressure of 1860 psia.

(U) The temperature and coolant flow data from the cooled chamber tests were analyzed and compared with the predicted values. The predicted overall coolant bulk temperature rises for the contoured walls and end plates were compared with the experimental values for water and N_2O_4 coolants. The end-plate data agreed extremely well with the predictions for both water and N_2O_4, while the contoured-wall rises were some 25 percent below the theoretical values (Fig. 5). In general, the experimental data agreed with the theoretical analysis (Fig. 2 and Table 1), within the scope of the assumption made and within the accuracy of the data. Because the integrated heat input appeared to be reasonably accurate, it was concluded that the predicted heat flux and hot-gas coefficient distributions along the test segment were reasonably correct.

(U) Epoxy resin was used as a seal in the joints between the contoured walls and end plates of the Hastelloy-X chamber. This material was used to seal against coolant and hot-gas leakage. No resin seal leaks were detected during the testing, and there was no indication of leakage after the chamber components were disassembled. Thus, the epoxy resin proved to be an acceptable seal. Material compatibility would be a problem, however, after extended periods of exposure to the hot gas and N_2O_4.

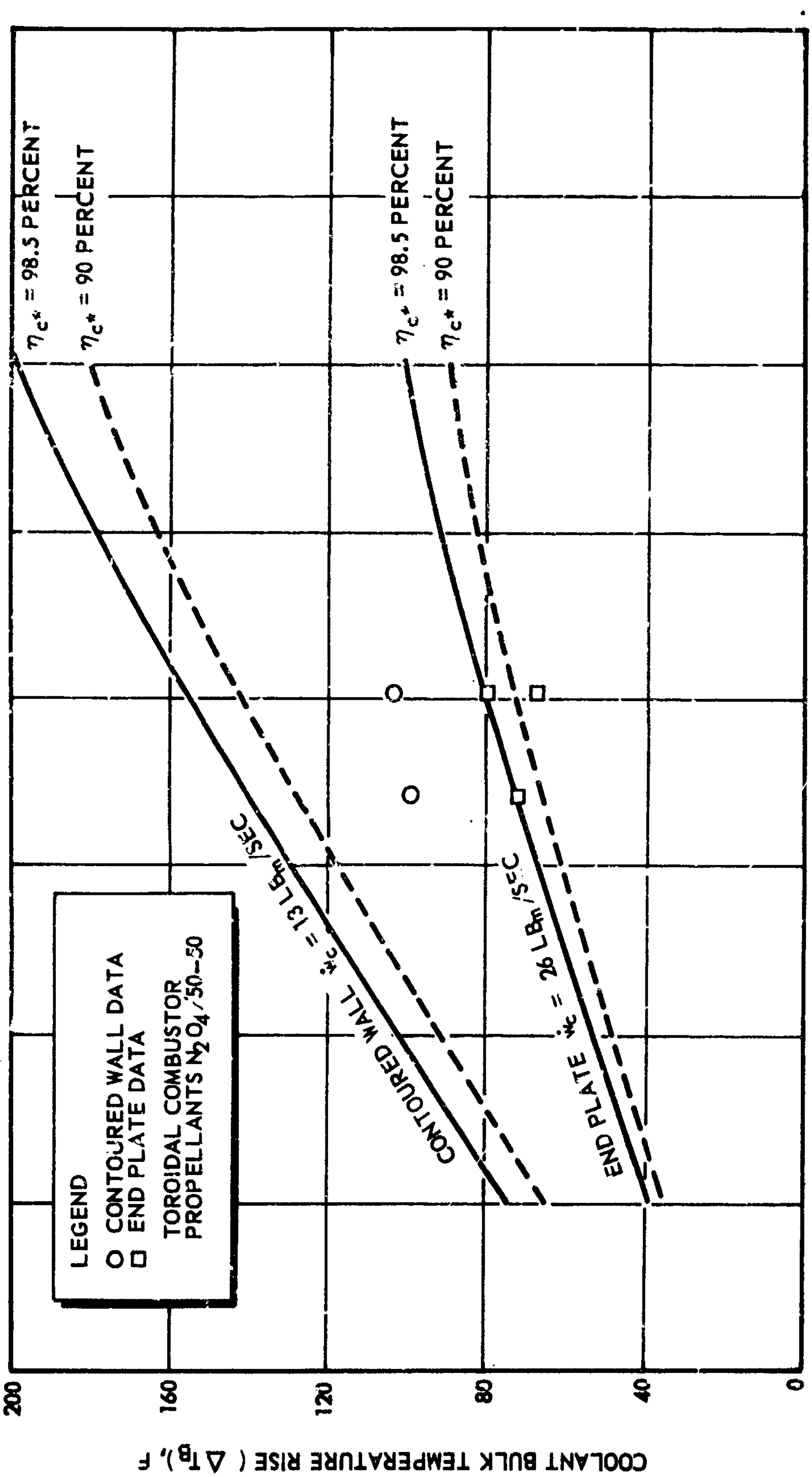

Figure 5. Comparison of Theoretical and Experimental N_2O_4 Coolant Bulk Temperature Rises for the Hastelloy-X Cooled Thrust Chamber

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1. AFRPL-TR-66-196 Final Report, Storable Toroidal Combustor Demonstration Program, August 1966, Rocketdyne, a Division of North American Aviation, Inc., Canoga Park, California, CONFIDENTIAL.

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DOCUMENT CONTROL DATA - R&D

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1. ORIGINATING ACTIVITY (Corporate author) Rocketdyne, a Division of North American Aviation, Inc., 6633 Canoga Ave., Canoga Park, California	2a. REPORT SECURITY CLASSIFICATION CONFIDENTIAL 2b. GROUP 4

3. REPORT TITLE

Final Report, Material and Processes R&D Report, Storable Toroidal Combustor Demonstration Program, Volume II

4. DESCRIPTIVE NOTES (Type of report and inclusive dates)

Final Report, 1 June 1965 through 30 June 1966

5. AUTHOR(S) (Last name, first name, initial)

Rocketdyne Engineering

6. REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
August 1966	19 & viii	1

8a. CONTRACT OR GRANT NO. AF04(611)-10916 Part I, Para. B; and Line Item of	9a. ORIGINATOR'S REPORT NUMBER(S) R-6678
b. PROJECT NO. DD1423	
c.	9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report) AFRPL TR-66-196
d.	

10. AVAILABILITY/LIMITATION NOTICES

11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY
	Air Force Rocket Propulsion Laboratory Research and Technology Division Edwards Air Force Base, California

13. ABSTRACT

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Toroidal Combustor						
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Storable Propellants						
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